A Unified Analysis of Radar Interferometry and Polarimetry for the Estimation of Forest Parameters

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1. INTRODUCTION

Radar interferometry is primarily sensitive to the spatial distribution of the scatterers constituting vegetated terrain [1], while polarimetry is primarily sensitive to their shape and orientation [2]. For forests, there are obvious qualitative relationships between the spatial distribution and orientation of certain typical features. Ground surfaces, which are spatially localized at the bottom of a forest are also horizontally oriented. Leaf-branch volumes, which are frequently concentrated more at the middle and top of the forest, are more randomly oriented. Different admixtures of ground, ground-volume (including ground-trunk), and direct volume returns induce distinctive signatures in both interferometric and polarimetric data. This paper explores the potential for unifying interferometric and polarimetric data by simultaneous analysis in order to estimate vegetation and surface characteristics. Estimation of parameters from a combined data set, unified with a physical scattering model, has the potential for being more accurate than estimations from interferometry or polarimetry independently.

In this paper, "interferometry" will mean the acquisition and cross-correlation of complex signals at two different ends of a baseline, but with the same receive and transmit polarization at each end:

$$\text{Interferometric cross} - \text{correlation} \equiv\ <\hat{t}\cdot\vec{E}_{\hat{t}}(\vec{R}_1)\,\hat{t}\cdot\vec{E}_{\hat{t}}^*(\vec{R}_2)>$$
$$(1)$$

where $\vec{E}_{\hat{t}}(\vec{R}_1)$ is the field received at the 1-end of the baseline due to a transmitted field with polarization vector $\hat{t}$. "Polarimetry" means the acquisition and cross-correlation of complex signals at the *same* end of a base-

line (single transmitter/receiver), but with different receive and transmit polarizations for each field in the cross-correlation:

$$\text{Polarimetric cross} - \text{correlation} \equiv\ <\hat{p}\cdot\vec{E}_{\hat{t}}(\vec{R}_1)\,\hat{p}'\cdot\vec{E}_{\hat{t}'}^*(\vec{R}_1)>$$
$$(2)$$

with $\hat{p}$ the receive polarization of the first field in the cross-correlation, and $\hat{p}'$ and $\hat{t}'$ the receive and transmit polarization vectors, respectively, for the second field in the cross-correlation. The most general situation, "polarimetric interferometry" [3] is the acquisition and cross-correlation of complex signals at two different ends of a baseline, with different receive and transmit polarization at each end:

$$\text{Pol.} - \text{Int. cross} - \text{correlation} \equiv\ <\hat{p}\cdot\vec{E}_{\hat{t}}(\vec{R}_1)\,\hat{p}'\cdot\vec{E}_{\hat{t}'}^*(\vec{R}_2)>$$
$$(3)$$

In order to motivate the unified analysis of interferometry and polarimetry, the signatures of vegetation in both interferometric and polarimetric data are shown in the next section. Section 3 contains a demonstration of vegetation parameter (tree height) estimation from TOP-SAR [4] interferometry and associated polarimetry data acquired over the Boreas Southern Test Site. Section 4 is a summary.

2. THE INTERFEROMETRIC AND POLARIMETRIC SIGNATURES OF VEGETATION

The amplitude and phase of the interferometric cross-correlation each respond to the vertical distribution of vegetation scatterers. The more vertically distributed, the lower the cross-correlation amplitude, and the higher the phase, as illustrated in Figure 1 below. Each element
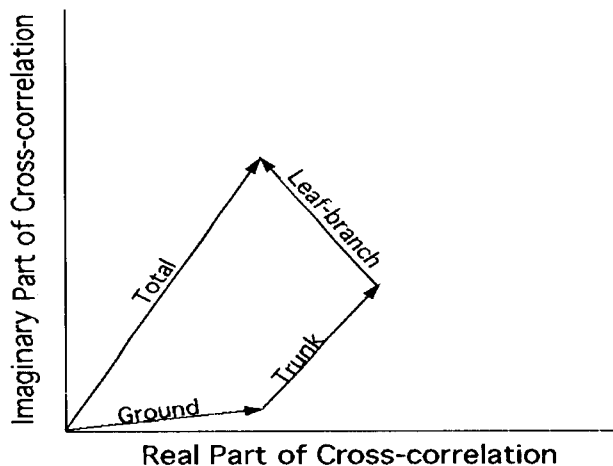
Figure 1: Schematic real and imaginary parts of the interferometric cross-correlation.

of forest vegetation, for example, contributes a phasor to the complex cross-correlation, with amplitude proportional to the product of the strength of the scattering at that element and the attenuation through the rest of the medium. The phase of the contributing element is proportional to the altitude of the element [1]. As Figure 1 shows, *vertically distributed vegetation will cause a decrease in cross-correlation amplitude* (relative to the zero-baseline amplitude, in which case all the phasors in Figure 1 add in a line) and *an increase in interferometric phase* (relative to the bare surface phase).

The effect of vegetated surfaces on polarimetry depends on how "oriented" the vegetated surface is. For simplicity, it is assumed here that the vegetation itself is completely randomly oriented, and would therefore exhibit no pronounced difference between an HHHH (H-transmit, H-receive both fields in the polarimetric cross-correlation) or VVVV transmit-receive polarization combination. A smooth, horizontal ground surface is assumed, for which the horizontal reflection coefficient is bigger than the vertical. Only the ground-volume (including the ground-trunk) interaction will be considered, and not the direct ground return, which is frequently much smaller than the ground-volume. The HHHH/VVVV polarization ratio is the only polarimetric observable that will be considered in this paper. It is expected that the more dominant the ground-surface contribution, the larger the HHHH/VVVV ratio. The ground-volume return will also introduce a phasor contribution in Figure 1 that is similar to the "ground" contribution shown. When the ground-volume return dominates, the correlation amplitude will increase relative to the more distributed volume-scattering-only effect. When the ground-volume and the volume returns are comparable, the interferometric amplitude will de-

crease relative to volume scattering only. Both the effect of a ground surface in the interferometry and in the HHHH/VVVV polarization ratio are shown in Figure 2. It can be seen that, for intermediate values of tree height, the competing mechanisms cause the expected reduction in correlation amplitude relative to
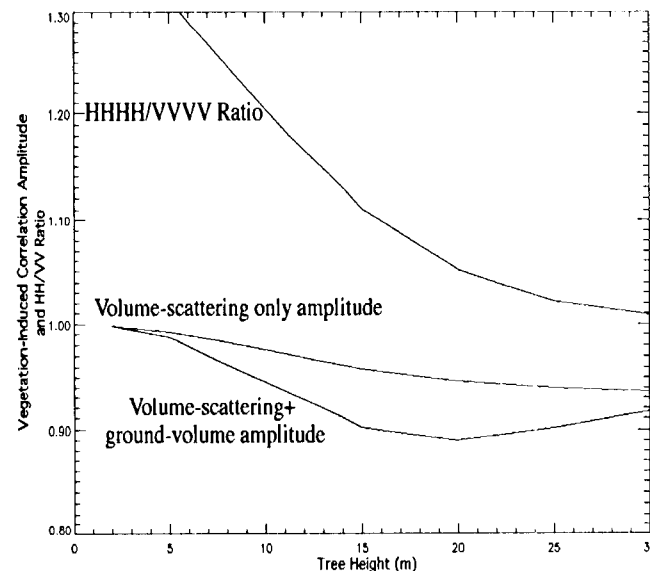

Figure 2: Calculated volume-only interferometric amplitude, volume + ground-volume amplitude, and polarimetric HHHH/VVVV ratio, versus tree height. Incidence angle=35°, baseline=5 m, extinction coefficient=0.4 db/m, wave length= 5 cm, and radar altitude=8 km.

the volume-scattering-only case. If correlation amplitude were being used to infer tree height, the ground-volume interaction, if it were not modeled, would cause a potentially severe overestimate of tree height (because the correlation amplitude would be low). Figure 3 demonstrates that the HHHH/VVVV ratio, which is high in this model when the ground-volume contribution is substantial, can help to identify the importance of the ground-volume contribution. A combined analysis of interferometry and polarimetry might therefore produce better results than the interferometry alone. The next section contains a combined analysis of TOPSAR data.

3. AN INTERFEROMETRIC-POLARIMETRIC DEMONSTRATION OF TREE-HEIGHT ESTIMATION

Figure 3 shows tree heights estimated from TOPSAR data collected over the Boreas Southern Test Site in "ping-pong" mode (effectively yielding two baselines of lengths 2.5 and 5 meters) in July 1995. Amplitudes and phases from both baselines were used to produce the indicated

"no ground estimation" tree heights. The estimated parameters were tree height, volume extinction coefficient, and underlying topography. For the "ground estimation" tree heights a single parameter having to do with the ground reflection coefficient and specular reflection characteristics of the volume was additionally estimated from the $\hat{t} = V$ TOPSAR interferometry.
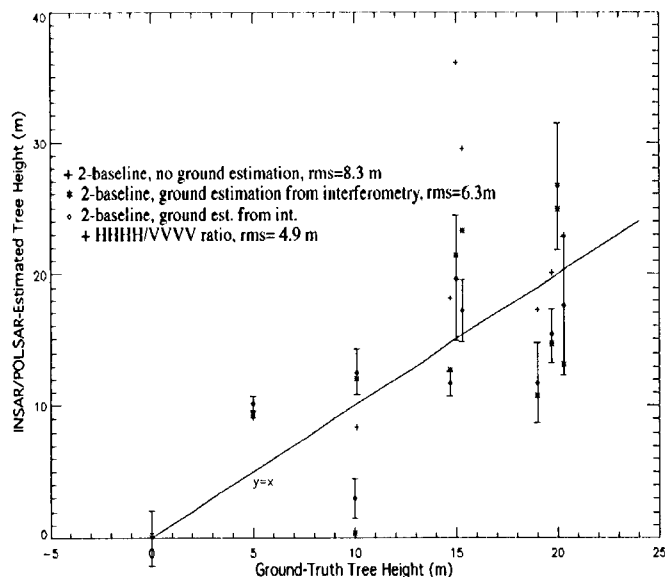
Figure 3: Tree heights estimated from TOPSAR plus polarimetric data from the Boreas Southern Test Site.

For the "ground estimation + HHHH/VVVV ratio" tree heights, the HHHH/VVVV ratio was also used in the parameter estimation, and the real part of the ground dielectric constant was additionally estimated (the imaginary part was assumed to be 1/3 of the real part, characteristic of soil). The polarimetric data were taken two years earlier, at the same time of year. This is obviously not optimal, but this was the only interferometric and polarimetric data available for this well-calibrated site, but coincident data are currently being processed and will be analyzed in the near future.

The results of Figure 3 are preliminary. There does appear to be an overestimation of the tree height for a few of the points when the ground-volume is not modeled. Both modeling the ground-volume in interferometry and introducing polarimetry seem to help. Figure 3 further suggests that using the HHHH/VVVV ratio improves the scatter about ground-truth tree heights. But there are corrections which have not yet been applied to the data, and the results could change. At the very least, Figure 3 suggests that ground-volume estimation and the HHHH/VVVV modeling are consistent with the trends in the data, and the combined interferometry-polarimetry data analysis approach taken in Figure 3 is promising.

4. SUMMARY

The signatures of a randomly oriented volume + a ground-volume in interferometric and polarimetric signals suggest that using interferometry and polarimetry together may provide useful estimates of vegetation properties. Introducing the ground-volume return further distributes the phase centers of the returns within the vegetation, and has the effect of lowering the correlation amplitude (and phase). Introducing the ground-volume return also increases the polarimetric HHHH/VVVV ratio. A simple model applied to Boreas Southern Test Site interferometric and polarimetric data shows rms tree-height accuracies of the order of 5 m. In the future, different approaches to phase calibrating these data will be tried and the analysis repeated, using all polarimetric quantities ($< HHVV^* >, < HVHV^* >$) etc. Multialtitude (simulating multibaseline) interferometric TOPSAR data will be taken along with polarimetric data between Santiam Pass and Camp Sherman in Oregon to further explore the combination of interferometry and polarimetry.

5. REFERENCES

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